RESOLUTION CONSULTANTS

To: Lora Fly, DON, NAVFAC MIDLANT

From: Brian Caldwell, P.G., Resolution Consultants

Subject: **Trigger Values Development - Addendum to the Operable Unit 2 (OU2) Offsite Groundwater Public Water Supply Contingency Plan (PWSCP)**

Date: July 15, 2015

Attachments:

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Introduction

Operable Unit 2 consists of volatile organic compounds (VOCs) that have contaminated groundwater beneath the Navy's former 105 acre parcel, and VOC-contaminated groundwater that has migrated south and east off-property. It becomes mixed with contamination originating on the NG property and forms a 3,000-acre plus area of VOC-contaminated groundwater plumes at varying depths that extend south of Hempstead Turnpike. The groundwater contamination extends to a depth of approximately 750 feet but is not continuous throughout this area and is not present at all depths. Other non-OU2 sources of groundwater contamination that are known or believed to be contributing to the OU2 plumes include the Bethpage Community Park OU3 groundwater, Hooker Ruco Superfund Site, and potentially other smaller releases.

The Navy is conducting environmental investigation and cleanup under the Navy's Environmental Restoration Program (ERP), in compliance with the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The OU2 groundwater contamination was addressed in the Navy 2003 Record of Decision (ROD) (NAVFAC, 2003). The ROD specifies that the selected remedy includes institutional controls, groundwater remediation, and a Public Water Supply Protection Program as defined in the Public Water Supply Contingency Plan (PWSCP, Arcadis, 2003).

Outpost monitoring wells, designed and located to serve as early warning wells, are to be installed and monitored as an element of the Public Water Supply Contingency Plan (PWSCP, Arcadis, 2003). One component of the outpost monitoring well system is the development of "trigger values", or concentration values for contaminants of concern in the OU2 ROD(NAVFAC 2003).

The PWSCP (Arcadis, 2003) included trigger values for nine proposed outpost wells. These wells were subsequently installed and are monitored quarterly by Northrop Grumman. In 2011, three additional outpost wells (BPOW 1-4, BPOW1-5, and BPOW1-6) were installed for South Farmingdale Water District (SFWD) Plant 1 to provide additional evaluation of groundwater north of the plant. In 2011, one additional outpost well (BPOW2-3) was installed for SFWD Plant 3 to allow additional evaluation of deeper groundwater north of the plant. Also, in 2011, two additional outpost wells (BPOW3-3 and BPOW3-4) were installed north of the New York American Water - Seamans Neck Road Plant and west of SFWD Plant 3 to allow evaluation of groundwater that may be intercepted by both plants. Trigger values for these outpost wells will be developed in a subsequent addendum. Since 2011, an additional 13 outpost wells have been installed (Table 1 and Figure 1).

The purpose of this report is to develop preliminary trigger values for two sets (13 total) of outpost monitoring wells installed to provide an early warning that VOCs from the OU 2 plume may impact South Farmingdale Water District Plant 6, Wells 8664 and 8665 or Massapequa Water District Wells 6442 and 6443. The trigger values should provide a minimum of 5 years notice before the VOCs are detected at a concentration of 0.5 ug/L in the water supply. These trigger values will be replaced with final trigger values when location-specific pumping tests are performed to allow more accurate measurements of connectivity and hydrogeology. Ten of the outpost wells were installed by Resolution Consultants in 2014 and 2015. Three outpost wells (BPOW5-1, BPOW5-2, BPOW5-3) were installed by Tetra Tech in 2012.

Site hydrogeology

Overburden at the site consists of well over 1,000 ft of Cretaceous deposits overlying crystalline bedrock of the Hartland Formation. Overburden is divided into four geologic units: the upper Pleistocene deposits, the Magothy Formation, the clay member of the Raritan Formation ("Raritan Clay") and the Lloyd Sand member of the Raritan Formation ("Lloyd Sand") (McClymonds and Franke, 1992).

The upper Pleistocene ranges in thickness from approximately 50 to 100 ft and consists of till and outwash deposits of medium to coarse sand and gravel with lenses of fine sand, silt and clay (Smolensky and Feldman, 1990); these deposits form the Upper Glacial Aquifer. Directly underlying this unit is the Magothy Formation with a thickness of 650 to 900 ft bgs. The Magothy is characterized by fine to medium sands and silts interbedded with zones of clays, silty sands and sandy clays. Sand and gravel lenses are found in some areas between depths of 600 and 880 ft bgs; these deposits form the Magothy Aquifer.

Investigations performed by the Navy indicate that the bottom of the Magothy (top of the Raritan Clay) can extend to depths of 700 to greater than 1,000 ft bgs. The Raritan Clay Unit consists of clay, silty clay, clayey silt, and fine silty sand and reportedly acts as a confining layer over the Lloyd Sand Unit.

The Magothy Aquifer is the major source of public water in Nassau County. The most productive water bearing zones are the discontinuous lenses of sand and gravel that occur within the siltier matrix located in the lower portion of the Magothy.

Groundwater flow is assumed to be primarily horizontal because of the stratified nature of the sand and gravel lenses and thin silty/clayey layers thought to reduce vertical flow. However water supply wells in the area with high withdrawal rates impose a pumping stress at depth that likely induce some vertical flow within their area of influence.

Trigger values for outpost wells have been developed through groundwater modeling. The complex geology and pumping stresses that exist at the Bethpage site present challenges for estimating contaminant fate and transport. Simulating plume arrival times and concentrations with a model involves many uncertainties and assumptions, and should be regarded as approximate. Using conservative hydraulic parameters, the model can be applied to estimate plume movement and develop an early warning system for public supply wells with outpost wells.

Modeling approach and modeling platform

The approach to develop trigger values for the outpost wells is to apply an analytical model to simulate transport from each outpost well to the supply wells. Figure 2 depicts the geometry of the model approach in which the source is located at the outpost well and transport is simulated from the outpost well to the supply well. An analytical model is constructed for each of the seven outpost wells (or well clusters). Applying appropriate aquifer parameters, the model is run iteratively to solve for and estimate what the concentration at the outpost well will be that results in a detection of 0.5ug/L at the associated supply well, allowing for a 5 year travel time.

The primary assumptions of this approach include:

1. Assuming that the "source" for this detection is an upgradient outpost well; source length is the distance from outpost well to supply well as shown on Figure 2 (locations approximate pending final survey); source width is the distance from the midpoints between adjacent outpost wells;
2. Assuming the source thickness at the outpost well will be approximated as the screen length of the supply well;
3. Assuming no retardation and no decay; and
4. The model simulates advective travel and attenuation through longitudinal and transverse dispersion.

This approach is conservative for the following reasons:

- No biodegradation or adsorption;
- Negligible vertical dispersion; and
- Does not account for the dilution of plume concentrations with other non-contaminated water in the capture zone of the supply well

Resolution used the Quick Domenico (QD) analytical fate and transport model to develop trigger values. The analytical steady state solution to the groundwater flow equation was first proposed by Domenico (Domenico,1987). The software platform for the Domenico solution is provided for download by the Pennsylvania Department of Environmental Protection (PDEP).

Quick Domenico (QD) calculates the concentration of contaminant species at any point and time downgradient of a source area of known width, thickness and strength. The kinds of contaminants for which QD is intended are dissolved organic contaminants whose fate and transport can be described or influenced by advection and lateral and vertical dispersion. For spatial resolution within the model, QD calculates the concentrations in a two dimensional 5x10 grid whose length and width are set by the user.

Key assumptions within the modeled area are:

1. Aquifer properties are homogeneous and isotropic;
2. Groundwater flow field is homogeneous and unidirectional;
3. Groundwater flow is steady state; and
4. Contaminant source remains constant in time.

Details of the solution in the Quick Domenico software and input parameters are provided in Appendix 1.

Model development and input parameters

Model inputs were a combination of site-specific data for the OU2 offsite groundwater data and literature values as appropriate. Where a range of values were available, conservative values were chosen. Table 2 provides a summary of the input parameters required within the model software. A few key aquifer parameters are discussed below.

Hydraulic conductivity (K):

Groundwater velocity (distance over time) is proportional to hydraulic conductivity (k), thus higher values of K predict faster travel time. To achieve conservative results, the highest reasonable K value of 75 ft/day was chosen based on the following references:

- The average K for the Magothy aquifer on Long Island is 56 ft/day (McClymonds and Franke, 1972);
- The K used in the calibrated USGS Bethpage model is 50 ft/day for the Upper Magothy and is 75 ft/day for the Basal Magothy (Misut, 2013);
- A pumping test conducted in 2013 at BWD6-2 yielded a K of 35 - 55 ft/day, based on 400 ft saturated thickness (TetraTech, 2014).

Gradient:

Groundwater velocity (distance over time) is also proportional to hydraulic gradient, thus higher gradient values predict faster travel time. Numerous gradient estimates were compared to choose a representative but conservative gradient of 0.002 for the model:

- Tetra Tech cites an antecedent gradient of approximately 0.002 in the vicinity BWD Plant 6 prior to their 2014 pumping test at BWD 6-2;
- An average gradient of approximately 0.0019 was estimated over the entire Bethpage site based on December 2014 and March 2015 water levels collected during Navy Quarterly groundwater monitoring;
- An average gradient of approximately 0.0018 was estimated between BPOW5-2/ BPOW5-3 and TT102D/TT102D2 wells, based on December 2014 and March 2015 water levels collected during Navy Quarterly groundwater monitoring;
- An average gradient of approximately 0.0011 was estimated between BPOW5-2/ BPOW5-3 and BPOW6-3/BPOW6-4 wells, based on December 2014 and March 2015 water levels collected during Navy Quarterly groundwater monitoring.

Porosity:

Groundwater velocity (distance over time) is inversely proportional to porosity, thus lower porosity values predict faster travel time The USGS DRAFT report on the calibrated numerical groundwater model for the Bethpage site references values ranging from 0.15 and 0.35 (Misut, 2013). A value of 0.15 was chosen as conservative value within this range.

Model Results

The model simulations provide an estimate of the trigger concentrations at each outpost well predicted to result in a detection of approximately 0.5 ug/L in the down gradient supply well in 5 years. The following inputs were selected to provide an estimate of trigger values:

- No biodegradation or adsorption;
- Negligible vertical dispersion;
- Does not account for dilution of plume with other non-contaminated water in the capture zone of the supply well;
- Hydraulic conductivity of 75 ft/day is on the high end of the range of composite Ks;
- Gradient of 0.002 is on the high end of the range for estimated gradients on site; and
- Porosity of 0.015 is on the low end of the range of estimated porosities for the site.

The resultant groundwater (seepage) velocity calculated by the QD model based on the above aquifer parameters is 365 ft/yr (1 ft/day).

Table 3 shows model results for the SFWD outpost wells (BPOW5-1, BPOW5-2, BPOW5-3, BPOW5-4, BPOW5-5, BPOW5-6, BPOW5-7) and for the MWD outpost wells (BPOW6-1, BPOW6-2, BPOW6-3, BPOW6-4, BPOW6-5, BPOW6-6). The table summarizes the distance from each outpost well to the downgradient supply well, the source width, and the trigger concentration. Model output is provided in Appendix 2 and 3.

Trigger concentrations at outpost wells upgradient of the SFWD wellfield ranged from 0.7 ug/L at the closest upgradient outpost wells (BPOW5-5, and BPOW5-6) to 1.4 ug/L at the furthest upgradient well (BPOW5-4). Trigger concentrations at outpost wells upgradient of the MWD wellfield ranged from 1.6 ug/L at the closest upgradient outpost wells (BPOW6-5 and BPOW6-6) to 2.8 ug/L at the furthest upgradient wells (BPOW6-3, BPOW6-4).

Trigger values are slightly higher at MWD outpost wells than at the SFWD outpost wells because the former are located further upgradient from the supply wells. Trigger values are directly proportional to the distance between the outpost well and the supply well: the further away the outpost well, the more lead time is provided and thus the higher the “warning” concentration will be before a detection of 0.5 ug/L is predicted to result at the supply well.

Sensitivity Analysis

A sensitivity analysis was conducted to determine how much the model predictions changed in response to changes in input parameters. Table 4 summarizes the analysis based on the model simulations of the BPOW6-3, BPOW6-4 well cluster. The following observations can be made about the effect of the parameter changes on predicted downgradient concentrations and trigger values:

- Source thickness has no effect
- Source width has a slight effect: increasing and decreasing source width by a factor 1.5 results in a trigger concentration change of -0.2ug/L and +0.4 ug/L, respectively.
- Dispersion has a significant effect:
  - reducing lateral dispersion by a factor of 1.5 (from Ax = 269 to Ax = 180) creates a steep plume front, decreases downgradient concentrations and increases the trigger concentration from 2.8 ug/L to 3.6 ug/L;
  - reducing lateral dispersion by a factor of 13 (from Ax = 269 to Ax = 20), a default sometimes used, increases the trigger concentration of 770 ug/L;
- Hydraulic conductivity (k), gradient (i) and porosity (n) are aquifer parameters that control groundwater (seepage) velocity and have a significant effect:
  - Increases in groundwater velocity (resulting from increases in K or i or decreases in n) result in higher downgradient concentrations, thus reducing the trigger concentration.
  - The greatest sensitivity of the model to increasing/decreasing any of the aquifer parameters by a factor of 1.5 was to decreasing the gradient, which increased the trigger concentration from 2.8 ug/L to 95 ug/L.
  - Increasing/decreasing any of the aquifer parameters by a factor of 1.5 resulted in the groundwater (seepage) velocity, originally 1 ft/day, to range from 0.5 to 1.5 ft/day. The resulting trigger concentration ranged from 95 ug/L to 1 ug/L, respectively.
  - To determine the sensitivity of trigger values to high velocity, a scenario was run with k = 75 ft/day, porosity = 0.1 and gradient = 0.003 (v = 2.25 ft/day), resulting in a trigger concentration of 0.63 ug/L.

Model Limitations

The following are limitations to applying the QD model:

- The model assumptions discussed above describe the approach of the Quick Domenico model and constrain the model's ability to represent site conditions.
- There is a significant volume of data for the Bethpage site, but understanding the fate and transport of the OU2 plume is not yet complete. Small-scale heterogeneities over the scale of a deep 700+ foot aquifer can influence plume fate and transport, thus predicting plume arrival times is uncertain in settings such as Bethpage. Such heterogeneities are not represented in the model.

If the above limitations are understood, the modeling is constructive in that it applies a uniform set of conservative parameters to estimate plume movement and to develop early warning values for public supply wells with associated outpost wells. .

References

Arcadis, 2000. Groundwater Feasibility Study, NY site 130003A and site 130003B (NYSDEC Doc 517)

Arcadis, 2003. Public Water Supply Contingency Plan (NYSDEC Doc 743)

Domenico, P.A., 1987. An Analytical Model For Multidimensional Transport of a Decaying Contaminant Species, Journal of Hydrology, 91, pp 49-58.

McClymonds and Franke, 1972. Water Transmitting Properties of Aquifers on Long Island, USGS Prof Paper 627E.

Misut, P., 2013 DRAFT. Simulation of zones of contribution to wells at Navy Water Treatment plant GM-38, Bethpage, NY, USGS.

Naval Facilities Engineering Command (NAVDAC), 2003. Record of Decision of Operable Unit 2 Groundwater NYS Registry: 1-30-003B Naval Weapons Industrial reserve Plant Bethpage, New York, April.

Pennsylvania Department of Environmental Protection, 2014. User's Manual for the Quick Domenico Groundwater Fate-and-Transport Model, Version No. 3b, February.

Technical Team for Optimization of the Bethpage Remedy, 2011. Remedy Optimization Team Report for the Bethpage Groundwater Plume Remedy, June.

Tetra Tech, 2014. Technical Memo: BWD 6-2 Aquifer Pumping Test/Capture one Analysis, NWIRP Bethpage, NY, March.

Table 1. Outpost Well Construction Summary

PWS Affiliation	Outpost Well	Total Depth (ft bgs)	Top of Screen (ft bgs)	Bottom of Screen (ft bgs)	VPB affiliation
Wells with trigger values developed in PWSCP (Arcadis, 2003)					
SFWD Wells 4043, 5148, 7377 (Plant 1)	BPOW1-1	241	196	241	VPB45
	BPOW1-2	335	310	335	
	BPOW1-3	419	374	419	
SFWD Well 6150 (Plant 3)	BPOW2-1	400	360	400	VPB130
	BPOW2-2	495	455	495	
ANY Wells 8480, 9338	BPOW3-1	516	446	516	none
	BPOW3-2	647	612	647	
LWD Well 5303	BPOW4-1	692	652	692	VPB46
	BPOW4-2	765	725	765	
Wells installed after 2003; trigger values developed in this document					
SFWD Wells 8664, 8665 (Plant 6)	BPOW5-1	515	480	510	VPB132
	BPOW5-2	585	540	580	
	BPOW5-3	665	620	660	
	BPOW5-4	575	545	570	VPB151
	BPOW5-5	545	515	540	VPB152
	BPOW5-6	615	585	610	
	BPOW5-7*	(555)	(525)	(550)	VPB153
MWD Wells 6442, 6443	BPOW6-1	580	550	575	VPB145
	BPOW6-2	785	755	780	
	BPOW6-3	780	750	775	VPB146
	BPOW6-4	575	545	570	
	BPOW6-5	555	525	550	VPB147
	BPOW6-6	800	770	795	

* BPOW5-7 construction design; installation underway

ANY = Aqua New York

LWD = Levittown Water District

MWD = Massapequa Water District

PWS = Public Supply Wells

SFWD = South Farmingdale Water District

Table 2. Input parameters for Quick Domenico analytical model

Parameter	Value	Explanation of value	Source
Source concentration (ug/L) "Trigger Value"	C	concentration input at source that results in detection of 0.5 ug/L at downgradient supply well after 5 years travel time	Determined by trial through Quick Domenico modeling
Distance downgradient of model concentration output	unique for each OW; see table 3	Travel distance from OW to supply well; location of model predicted concentration	project mapping
Source width (ft)	unique for each OW; see table 3	distance from the midpoints between adjacent outpost wells	project mapping
Source thickness (ft) - SFWD wells	100 ft	use combined screen intervals of SFWD-8664 (506-576 ft bgs) and SFWD-8665 (529-606 ft bgs) as approximate thickness of source at concentraton indicated	Arcadis Groundwater Feasibility Study, NY site 130003A and site 130003B, 2000 (NYSDEC Doc 517)
Source thickness (ft) - MWD wells	168 ft	use combined screen intervals of MWD-6442 (524-612 ft bgs) and MWD-6443 (770-850 ft bgs) as approximate thickness of source at concentraton indicated	Arcadis PWS Contengency Plan, 2003 (NYSDEC Doc 743)
Time (days)	1825	5 years	In accordance with Arcadis Public Water Supply Contingency Plan (2003)
longitudinal dispersivity A(x)	unique for each OW; see table 3	typically 1/10 plume length	Estimated utilizing EPA methodology (http://www.epa.gov/athens/learn2model/part-two/onsite/longdisp.html)
transverse dispersitivity A(y)	unique for each OW; see table 3	typically 1/10A(x)	Quick Domenico Manual, 2014
vertical dispersivity A(z)	unique for each OW; see table 3	typically 1/1000 A(y); default value is conservative and approximates 2-dimensional transport	Quick Domenico Manual, 2014
hydraulic conducitivity (k) (ft/d)	75	Applied the highest reasonable K value for conservative results, suppported by site data	1. McClymonds and Franke, 1972; 2. Tetra Tech, 2014; 3. Misut, 2013.
gradient (i)	0.002	use 0.002 from 2014 Tetra Tech pumping test	Tetra Tech, 2014
porosity (n)	0.15	conservative value within reasonable range of 0.15 and 0.35	Misut, 2013

Notes:
The QD model simulations will be conservative in assuming no biodegredation or adsorption
Resultant groundwater (seepage) velocity = 1 ft/day

Table 3. Quick Domenico model results

SFWD Plant 6	BPOW5-1, 5-2, 5-3	BPOW5-4	BPOW5-5, 5-6	BPOW5-7
Distance from BPOW to SFWD Plant 6 wellfield (ft)	1983	2136	1424	1576
Source width (ft)	1730	1830	1322	1627
Dispersion Ax, Ay, Az	198 / 19.8 / 0.019	213 / 21.3 / 0.021	142 / 14.2 / .014	157 / 15.7 / .015
Trigger concentration (ppb) at BPOW	**1.2**	**1.4**	**0.7**	**0.8**

MWD Plant Wells 4 and 5	BPOW6-1, 6-2	BPOW6-3, 6-4	BPOW6-5, 6-6
Distance from BPOW to MWD Wells 4 and 5 (ft)	2237	2695	2237
Source width (ft)	966	1526	1526
Dispersion Ax, Ay, Az	223 /22.3 / 0.022	269 / 26.9 / 0.026	223 / 22.3 / 0.022
Trigger concentration (ppb) at BPOW	**1.8**	**2.8**	**1.6**

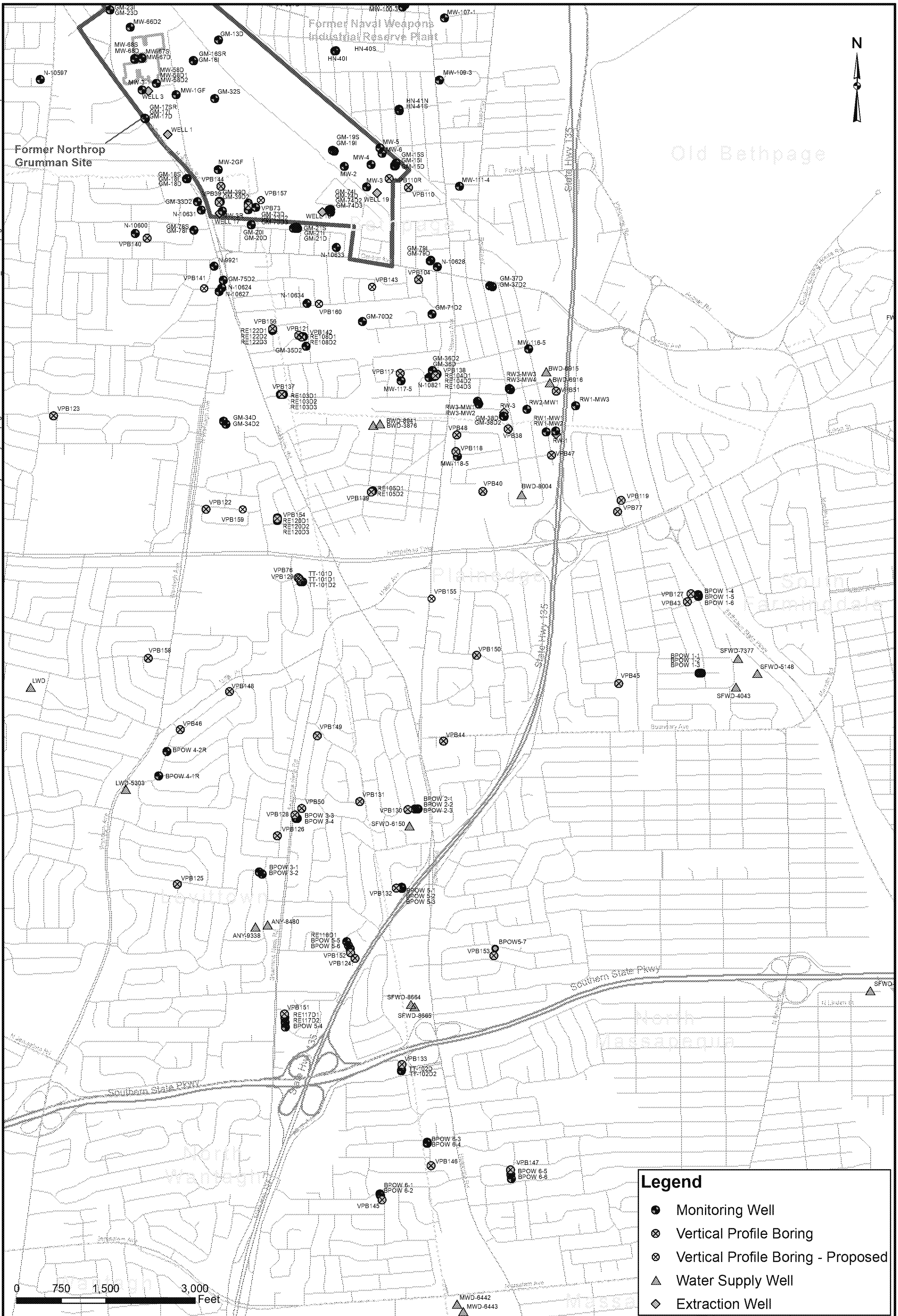
Note:
Trigger concentration: contaminant concentration at BPOW estimated to result in 0.5 ug/L detection at Water supply well after 5 years travel time using analytical Quick Domenico fate and transport model (see text for assumptions and limitations).

Table 4. Sensitivity analysis

	Inputs							Model Prediction
	K (ft/d)	i	n	v (ft/d)	Dispersion: Ax/Ay/Az	Source thickness (ft)	Source width (ft)	OW trigger conc (ug/L)
Base model BPOW6-3, BPOW6-4	**75**	**0.002**	**0.15**	**1**	**269/26.9/.027**	**168**	**1526**	**2.8**
Sensitivity to source thickness (x 1.5, ÷1.5)	75	0.002	0.15	1	269/26.9/.027	**112**	1526	2.8
	75	0.002	0.15	1	10/1/.001	**252**	1526	2.8
Sensitivity to source width (x 1.5, ÷1.5)	75	0.002	0.15	1	269/26.9/.027	168	**2290**	2.6
	75	0.002	0.15	1	269/26.9/.027	168	**1018**	3.2
Sensitivity to dispersion (÷1.5, ÷13)	75	0.002	0.15	1	**180/18/.0018**	168	1526	3.6
	75	0.002	0.15	1	**20/2/0.002**	168	1526	770
Sensitivity to K, i, n (x 1.5, ÷1.5)	**112**	0.002	0.15	1.5	269/26.9/.027	168	1526	1
	50	0.002	0.15	0.67	269/26.9/.027	168	1526	15
	75	**0.003**	0.15	1.5	269/26.9/.027	168	1526	1
	75	**0.001**	0.15	0.5	269/26.9/.027	168	1526	95
	75	0.002	**0.225**	0.67	269/26.9/.027	168	1526	15
	75	0.002	**0.1**	1.5	269/26.9/.027	168	1526	1
High velocity scenario	75	0.003	0.1	2.25	269/26.9/.027	168	1526	0.63

Trigger concentration: contaminant concentration at BPOW estimated to result in 0.5 ug/L detection at Water supply well after 5 years travel time using analytical Quick Domenico fate and transport model (see text for assumptions and limitations).

Sensitivity analysis based on BPOW6-3 and BPOW6-4 inputs
Other BPOW6-3, BPOW6-4 inputs:
Length (distance from OW to MWD) = 2695 feet



NAVFAC

Figure 1. Well Location Map

NAVAL WEAPONS INDUSTRIAL RESERVE PLANT
BETHPAGE, NEW YORK

CONTRACT NUMBER	CTO NUMBER
N62470-11-D8013	WE15
APPROVED BY EV	DATE 6/16/2015
APPROVED BY —	DATE —
FIGURE NO. 1	REV 0

ED_002631A_00004386-00013

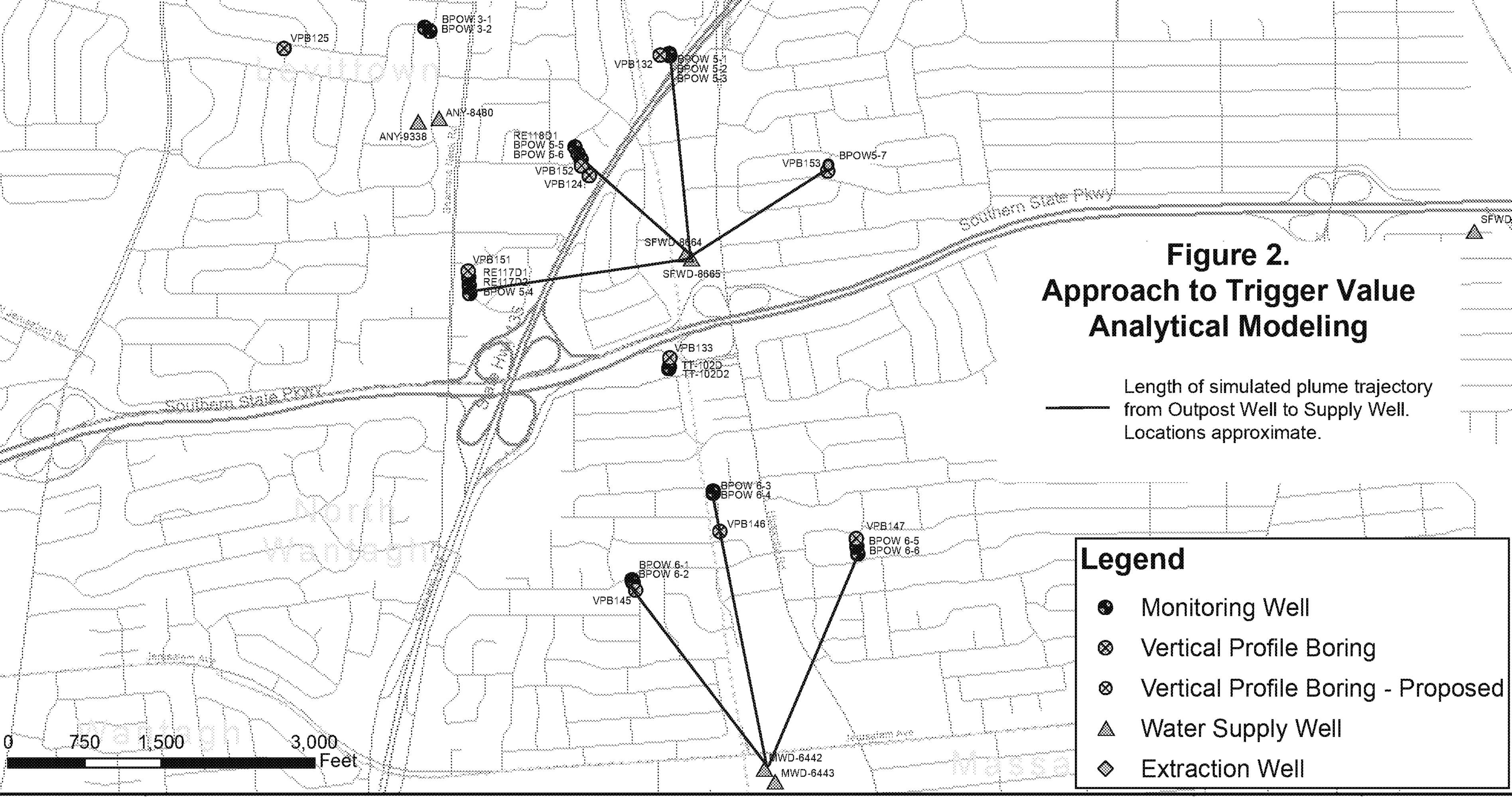


Figure 2. Approach to Trigger Value Analytical Modeling

Appendix 1. Quick Domenico

The following is excerpted from an update to the model provided by the PADEP (2008):

Quick Domenico.xls (QD) is a Microsoft Excel spreadsheet application of "An Analytical Model For Multidimensional Transport of a Decaying Contaminant Species", by P.A. Domenico, Journal of Hydrology, 91 (1987), pp 49-58. QD solves the following equation with two modifications discussed below:

$$C(x,y,z,t) = \left(\frac{C_o}{8}\right)\exp\left\{\frac{x}{2\alpha_x}\left[1-\left(1+\frac{4\lambda\alpha_x}{v}\right)^{\frac{1}{2}}\right]\right\}erfc\left\{\left[x-vt\left(\sqrt{1+4\lambda\alpha_x/v}\right)\right]/2\sqrt{\alpha_x vt}\right\}$$

$$\left\{erf\left[(y+Y/2)/2\sqrt{\alpha_y x}\right]-erf\left[(y-Y/2)/2\sqrt{\alpha_y x}\right]\right\}\left\{erf\left[(z+Z/2)2\sqrt{\alpha_z x}\right]-erf\left[(z-Z/2)/2\sqrt{\alpha_z x}\right]\right\}$$

where:

x = distance from planar source to the location of concern (i.e. property line) along the center line of the plume.
C(x,y,z,t) = the concentration of the contaminant at location x, y, z from the source at time t.
C_o = source concentration - the highest concentration of the contaminant in the groundwater at the source.
α_x = dispersivity in the x direction.
α_y = dispersivity in the y direction .
α_z = dispersivity in the z direction.
erf = error function
erfc = complementary error function
k= hydraulic conductivity.
i = hydraulic gradient
n_e = effective porosity (entered as a decimal fraction - (i.e. .25)
v = specific discharge. (ki/n_e)
λ =1st order decay constant.
S_w = width of source area. S_z = depth of source area.
x,y,z - these are the spatial coordinates in the horizontal, transverse and vertical directions that define the point or points where concentration information is desired.
t - this is time since the plume source started moving

In QD this equation has been modified in two ways. First, "v" has been modified to include a retardation factor defined as:

$1 + (KOC*foc*p_b / n_e)$.

where:

KOC = the organic carbon partition coefficient
foc = fraction of organic carbon expressed as a decimal percent
p_b = the dry bulk density of the aquifer matrix
and n_e = effective porosity .

Secondly, the term "Z/2" in the last two error function terms of the equation have been replaced by "Z" as described by Domenico (1987), page 53, to account for dispersion in the vertical axis in only the downward direction [and not the upward direction] as would occur with contaminants at the water table in a thick uniform aquifer and the source geometry for which this application is designed.

Appendix 2. Model Output,

South Farmingdale Water District Outpost Wells

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW5-1, 5-2, 5-3

Date: 6/1/2015 ~~Prepared by:~~ Resolution Consultants

Contaminant:

NEW QUICK_DOMENICO.XLS

SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

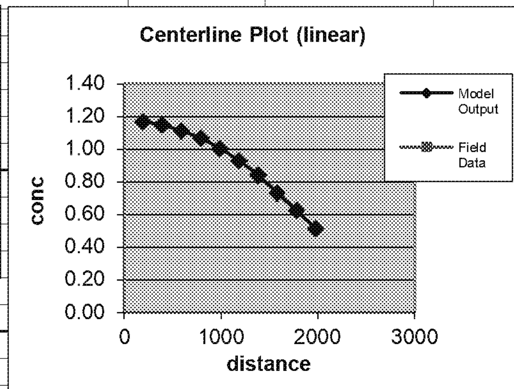
SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
1.2	1.98E+02	1.98E+01	1.90E-02	0	1730	100	1825

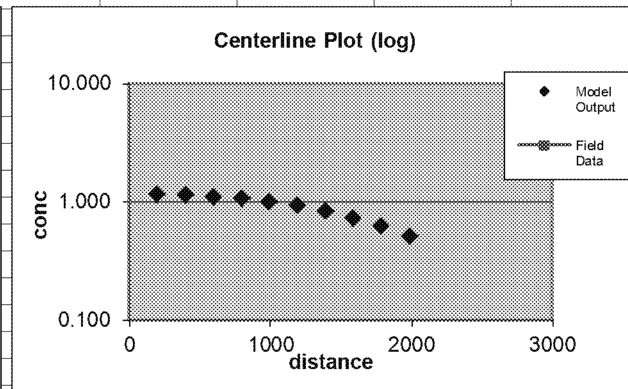
Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm^{3})	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

Point Concentration

x(ft)	y(ft)	z(ft)
1983	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	1983	0	0
at	1825	days =	**0.510** ug/l





AREAL CALCULATION MODEL DOMAIN

Length (ft) 1983

Width (ft) 1730

	198.3	396.6	594.9	793.2	991.5	1189.8	1388.1	1586.4	1784.7	1983
1730	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
865	0.583	0.572	0.556	0.533	0.502	0.464	0.418	0.366	0.311	0.256
0	1.167	1.144	1.111	1.065	1.004	0.927	0.835	0.732	0.622	0.510
-865	0.583	0.572	0.556	0.533	0.502	0.464	0.418	0.366	0.311	0.256
-1730	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001

Field Data:	Centerline CConcentration									
	Distance from Source									

ED_002631A_00004386-00018

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW5-4
Date: 6/1/2015 Prepared by: Resolution Consultants
Contaminant:

NEW QUICK_DOMENICO.XLS

SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

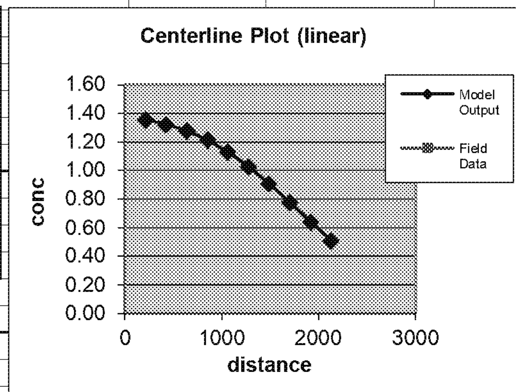
SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
1.4	2.13E+02	2.13E+01	2.10E-02	0	1830	100	1825

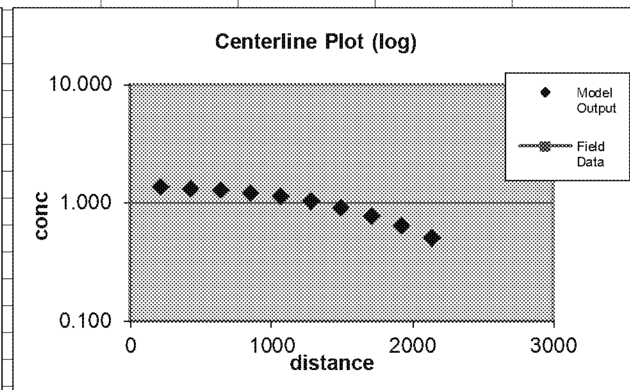
Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm^3)	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

Point Concentration

x(ft)	y(ft)	z(ft)
2136	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	2136	0	0
at	1825	days =	**0.506** ug/l





AREAL MODEL CALCULATION DOMAIN
Length (ft) 2136
Width (ft) 1830

	213.6	427.2	640.8	854.4	1068	1281.6	1495.2	1708.8	1922.4	2136
1830	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
915	0.676	0.660	0.637	0.605	0.563	0.512	0.452	0.387	0.319	0.254
0	1.353	1.321	1.275	1.210	1.127	1.024	0.904	0.773	0.638	0.506
-915	0.676	0.660	0.637	0.605	0.563	0.512	0.452	0.387	0.319	0.254
-1830	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001

Field Data:									
Centerline C Concentration									
Distance from Source									

ED_002631A_00004386-00019

Trigger concentration

NEW QUICK DOMENICO

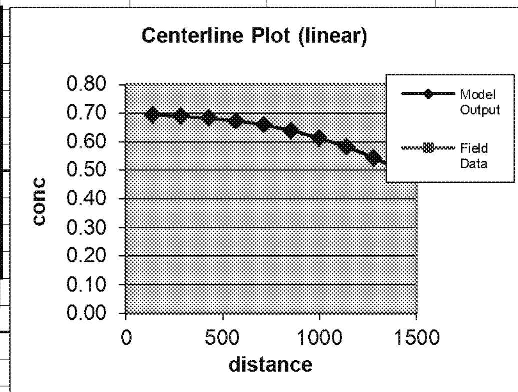
ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL							
Project:	Bethpage BPOW5-5, 5-6						
Date:	6/1/2015	Prepared by:	Resolution Consultants				
		Contaminant:					
SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
0.7	1.42E+02	1.42E+01	1.40E-02	0	1322	100	1825
Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm3)	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

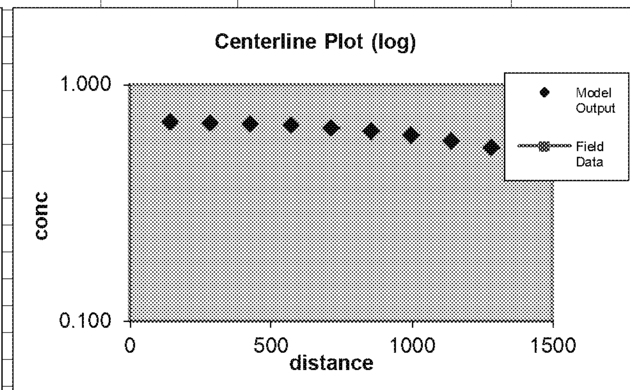
NEW QUICK_DOMENICO.XLS

SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES"
P.A. Domenico (1987)
Modified to Include Retardation

Point Concentration

x(ft)	y(ft)	z(ft)	
1424	0	0	
	x(ft)	y(ft)	z(ft)
Conc. At	1424	0	0
at	1825	days =	0.497 ug/l





AREAL MODEL CALCULATION DOMAIN
Length (ft) 1424
Width (ft) 1322

	142.4	284.8	427.2	569.6	712	854.4	996.8	1139.2	1281.6	1424
1322	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
661	0.347	0.344	0.341	0.336	0.329	0.319	0.306	0.290	0.271	0.249
0	0.693	0.689	0.682	0.672	0.657	0.638	0.612	0.581	0.542	0.497
-661	0.347	0.344	0.341	0.336	0.329	0.319	0.306	0.290	0.271	0.249
-1322	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Field Data:	Centerline C Concentration
	Distance from Source

ED_002631A_00004386-00020

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW5-7

Date: 6/1/2015 Prepared by: Resolution Consultants

Contaminant:

NEW QUICK_DOMENICO.XLS

SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

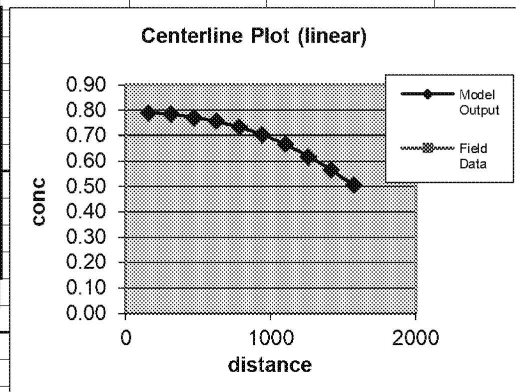
SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
0.8	1.57E+02	1.57E+01	1.50E-02	0	1627	100	1825

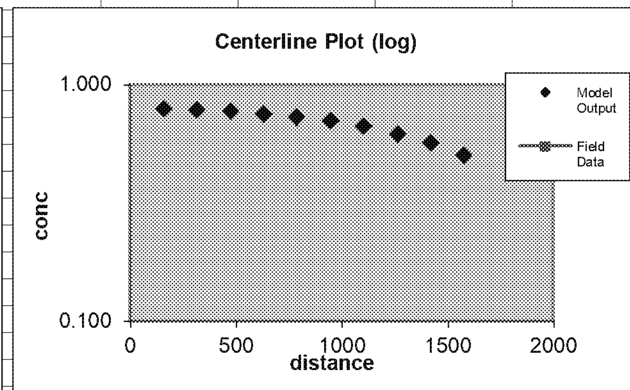
Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm^3)	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

Point Concentration

x(ft)	y(ft)	z(ft)
1576	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	1576	0	0
at	1825	days =	**0.503** ug/l





AREAL CALCULATION MODEL DOMAIN

Length (ft) 1576

Width (ft) 1627

	157.6	315.2	472.8	630.4	788	945.6	1103.2	1260.8	1418.4	1576
1627	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
813.5	0.394	0.391	0.385	0.377	0.366	0.351	0.332	0.309	0.282	0.252
0	0.789	0.782	0.770	0.754	0.732	0.702	0.664	0.618	0.563	0.503
-813.5	0.394	0.391	0.385	0.377	0.366	0.351	0.332	0.309	0.282	0.252
-1627	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Field Data: **Centerline CConcentration**

Distance from Source

Appendix 3. Model Output

Massapequa Water District Outpost Wells

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW6-1, 6-2

Date: 6/1/2016 Prepared by: Resolution Consultants

Contaminant:

NEW QUICK_DOMENICO.XLS

SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

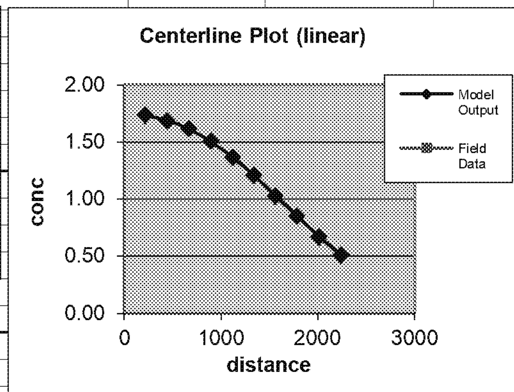
SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
1.8	2.23E+02	2.23E+01	2.20E-02	0	966	168	1825

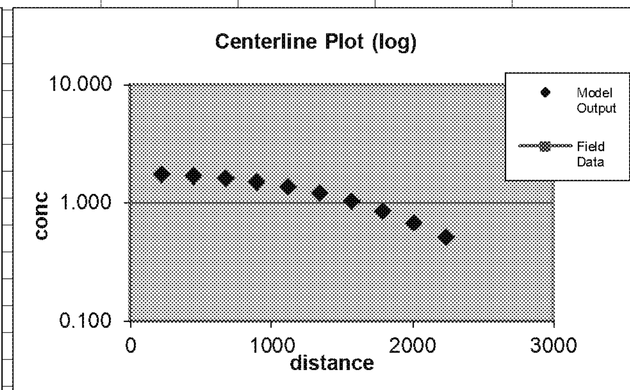
Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm3)	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

Point Concentration

x(ft)	y(ft)	z(ft)
2237	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	2237	0	0
at	1825	days =	**0.510** ug/l





AREAL MODEL CALCULATION DOMAIN

Length (ft) 2237

Width (ft) 966

	223.7	447.4	671.1	894.8	1118.5	1342.2	1565.9	1789.6	2013.3	2237
966	0.000	0.001	0.004	0.012	0.022	0.031	0.037	0.041	0.040	0.037
483	0.866	0.843	0.810	0.764	0.705	0.633	0.552	0.464	0.375	0.291
0	1.732	1.685	1.611	1.504	1.367	1.205	1.029	0.847	0.671	0.510
-483	0.866	0.843	0.810	0.764	0.705	0.633	0.552	0.464	0.375	0.291
-966	0.000	0.001	0.004	0.012	0.022	0.031	0.037	0.041	0.040	0.037

Field Data: **Centerline CConcentration**

Distance from Source

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW6-3, 6-4

Date: 6/1/2015 Prepared by: Resolution Consultants

Contaminant:

SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
2.8	2.69E+02	2.69E+01	2.60E-02	0	1526	168	1825

Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm3)	KOC	Frac. Org. Carb.	Retard-ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

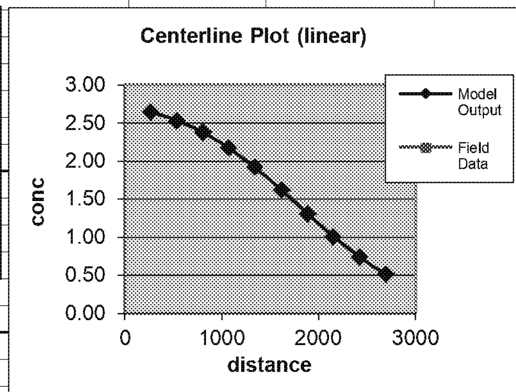
NEW QUICK_DOMENICO.XLS

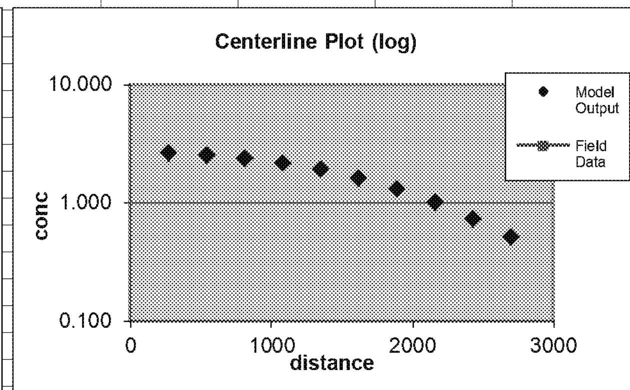
SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

Point Concentration

x(ft)	y(ft)	z(ft)
2695	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	2695	0	0
at	1825	days =	0.508 ug/l





AREAL MODEL CALCULATION DOMAIN

Length (ft) 2695

Width (ft) 1526

	269.5	539	808.5	1078	1347.5	1617	1886.5	2156	2425.5	2695
1526	0.000	0.000	0.000	0.002	0.004	0.008	0.011	0.013	0.013	0.012
763	1.318	1.264	1.187	1.084	0.959	0.816	0.665	0.517	0.381	0.266
0	2.637	2.528	2.372	2.165	1.909	1.617	1.309	1.008	0.736	0.508
-763	1.318	1.264	1.187	1.084	0.959	0.816	0.665	0.517	0.381	0.266
-1526	0.000	0.000	0.000	0.002	0.004	0.008	0.011	0.013	0.013	0.012

Field Data: Centerline C Concentration

Distance from Source

ED_002631A_00004386-00024

Trigger concentration

NEW QUICK DOMENICO

ADVECTIVE TRANSPORT WITH THREE DIMENSIONAL DISPERSION,1ST ORDER DECAY and RETARDATION - WITH CALIBRATION TOOL

Project: Bethpage BPOW6-5, 6-6

Date: 6/1/2015 Prepared by: Resolution Consultants

Contaminant:

SOURCE CONC (uG/L)	Ax (ft)	Ay (ft)	Az (ft) >=.001	LAMBDA day-1	SOURCE WIDTH (ft)	SOURCE THICKNESS (ft)	Time (days) (days)
1.6	2.23E+02	2.23E+01	2.20E-02	0	1526	168	1825

Hydraulic Cond (ft/day)	Hydraulic Gradient (ft/ft)	Porosity (dec. frac.)	Soil Bulk Density (g/cm^3)	KOC	Frac. Org. Carb.	Retard- ation (R)	V (=K*i/n*R) (ft/day)
7.50E+01	0.002	0.15	1.8	0	0.00E+00	1	1

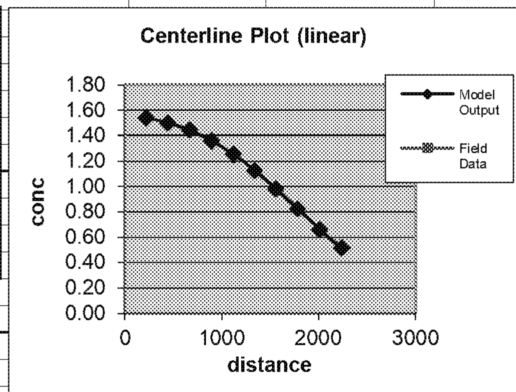
NEW QUICK_DOMENICO.XLS

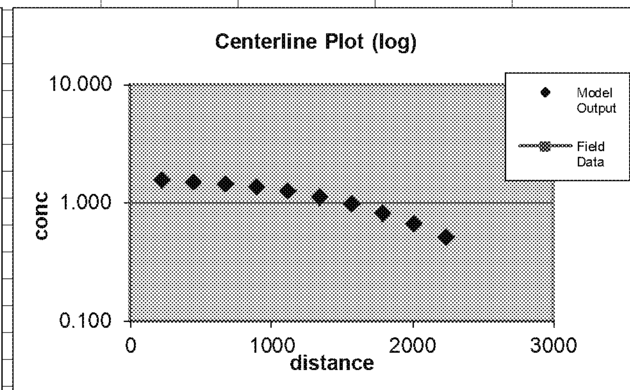
SPREADSHEET APPLICATION OF "AN ANALYTICAL MODEL FOR MULTIDIMENSIONAL TRANSPORT OF A DECAYING CONTAMINANT SPECIES" P.A. Domenico (1987) Modified to Include Retardation

Point Concentration

x(ft)	y(ft)	z(ft)
2237	0	0

	x(ft)	y(ft)	z(ft)
Conc. At	2237	0	0
at	1825	days =	0.510 ug/l





AREAL MODEL CALCULATION DOMAIN

Length (ft) 2237

Width (ft) 1526

	223.7	447.4	671.1	894.8	1118.5	1342.2	1565.9	1789.6	2013.3	2237
1526	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.004	0.004
763	0.770	0.749	0.720	0.679	0.627	0.563	0.490	0.413	0.334	0.259
0	1.539	1.499	1.439	1.358	1.252	1.124	0.977	0.819	0.660	0.510
-763	0.770	0.749	0.720	0.679	0.627	0.563	0.490	0.413	0.334	0.259
-1526	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.004	0.004

Field Data:								
Centerline C Concentration								
Distance from Source								